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ANNUAL TECHNICAL REPORT

4D INTERCONNECT EXPERIMENTAL DEVELOPMENT

16 December 1991

Sponsored by

USAF, Air Force Office
of Scientific Research
Bolling AFB, D.C. 20332-6448

Contract No. F49620-91-C-0002

Prepared by
Philip D. Henshaw
Steven A. Lis

"The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research."

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Abstract

This report summarizes the work performed during the first year of a two year program aimed at demonstrating the feasibility of constructing a 4-dimensional neural network based on the unique properties of spectral hole burning (SHB) materials. The work is progressing as originally planned with the basic optical system nearly complete and tested. The necessary SHB materials have been synthesized and excellent quality holograms have been recorded and retrieved. Both wavelength and angle multiplexing have been demonstrated with no apparent crosstalk. The system design has been precisely defined and all the key components have been selected. A discussion is presented describing a set of initial tests which are aimed at verifying the basic operational capabilities of the system. The next phase of complete system integration and testing will soon begin.

1 Introduction

This annual report provides a description of the program status of the first year of a two year program. The purpose of the program is to build and demonstrate the operability of a 4-dimensional neural network computer based upon the special capabilities of a holographically based optical system and Spectral Hole Burning materials (SHB) as the recording media. As described in our Phase I report [1=1], 4-dimensional capacity is required to fully connect two 2-dimensional planes in a sealable manner. In our architecture, the four dimensions are provided by the three spatial dimensions available using volume holographic recording plus the fourth dimension of laser wavelength. By appropriate system design, one of the input planes can be coded by laser wavelength to make use of this fourth dimension, as shown conceptually in Figure 1.

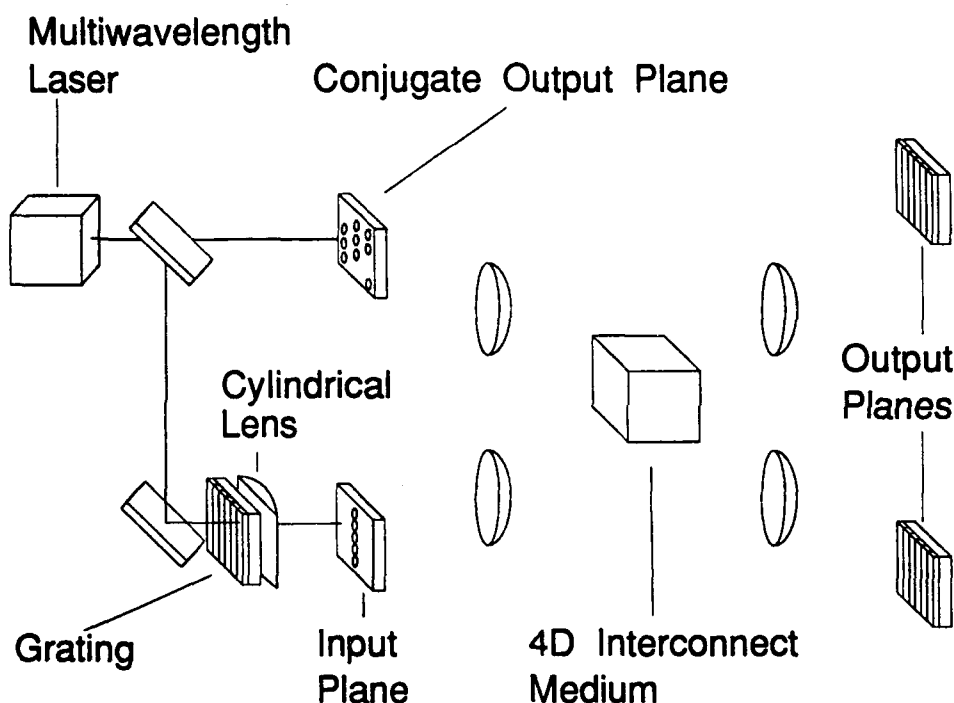


Figure 1. Conceptual diagram of the 4D neural network system based on SHB media.

The principal efforts of this first year of the program have been aimed at four tasks:

1. Preparing and examining some of the key aspects of the SHB media.
2. Building the neural network optical system (including tunable laser) and testing it for suitability as to holographic storage, of optical interconnects.
3. Planning the system software control and electronics hardware necessary for efficient operation of the demonstration system.
4. Planning the experimental tests of the system so that we may prove that the system operates as expected.

In the sections which follow, each of these subjects will be discussed in detail.

2 Preparation of SHB Media

The initial attempts at the preparation of SHB media suitable for use as a holographic storage medium have been successful. Polymer matrices based on both polystyrene (PS) and polymethyl methacrylate (PMMA) have been prepared of suitable optical quality and uniformity for our experimental needs. The introduction of the organic photochemical species entailed some subtleties, but has been successful. The information obtained, when coupled with the available literature, provides us with a relatively clear path to the preparation of numerous organic high performance SHB media.

2.1 Introduction

The principal goal of the materials preparation effort associated with this program is to provide a SHB sample of sufficient optical quality and which can be used to record holograms. Since a number of suitable candidates exist which have been previously studied by others, preparation of novel materials was not necessary. Based on arguments which have been stated previously [1] the porphyrins were identified as a class of materials providing suitable performance in terms of homogeneous and inhomogeneous linewidth, absorption cross section and quantum efficiency for conversion. The spectral range at which recording will be performed is determined principally by the selection of the specific porphyrin. Because of the wide range of porphyrins available (see Figure 2) our selection of operating wavelength was made based on optical considerations. For reasons of convenience it was decided to perform the initial studies at 633 nm (the HeNe wavelength). This was decided because of the relative ease of obtaining optical components coated for this wavelength and the convenience of using a simple HeNe laser for the initial experiments. It also turns out that chlorin (H_2Ch) is an SHB material which absorbs strongly in the wavelength range near 633 nm and has very interesting properties for both the near and long term with respect to erasability (which we shall not address here). For this reason, chlorin was selected as the principal material of interest, but we also undertook a small survey of related porphyrins in order to determine the level of effort generally required in the preparation of these materials by different means. To this end, we have also examined phthalocyanine (H_2Pc), porphine (H_2P), chlorin- e_6 (H_2Ch-e_6), and tetraphenylporphine (TPP).

The host materials which have been previously studied include polystyrene (PS), polymethyl methacrylate (PMMA), polyvinyl alcohol (PVA), polyethylene (PE) and a range of related polymers and copolymers. Most of the previous work has focused on the preparation of relatively thin films and often without concern for optical quality because simple absorptive properties were studied. However, high quality holograms were recorded in thick samples of PS [2] and some significant Japanese work has focused on the use of PMMA and related copolymers prepared from ethylene and methyl methacrylate.[3] Because optical components are often prepared from PS and PMMA (Plexiglass is a common trade name), we chose to center these early investigations on these two host materials.

A factor for consideration was the anticipated homogeneous linewidth obtained from the photochemical species in these hosts. Previous workers have shown that these materials have linewidths which are principally determined by the properties of the host polymer.[3,4] The properties of the tunable laser which we intend to use will define the laser linewidth to be roughly 300 MHz and a homogeneous linewidth of similar magnitude is appropriate. Our examination of the literature indicates that we can expect homogeneous linewidths of the order of 1 to 3 GHz at a temperature of 4 K.

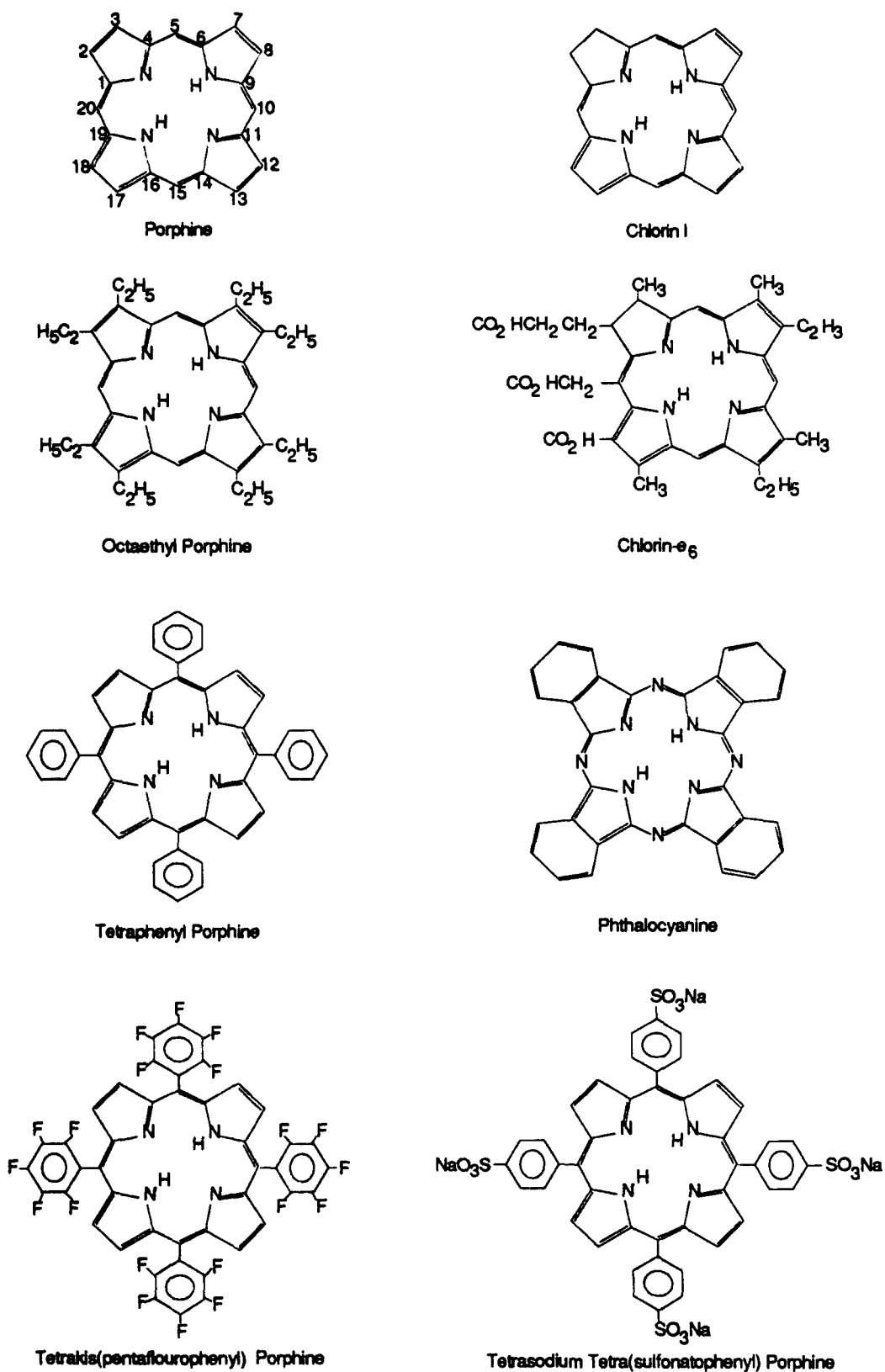


Figure 2. Chemical structures of the porphyrin compounds referred to in the literature as candidate SHB materials. Note that in the case of porphine, the numbering system of the carbon atoms has been highlighted. Of these, the first six porphyrins have already been incorporated into suitable polymers by us.

Based on this consideration of properties, H₂Ch in PS or in PMMA would be quite suitable. Preparation of a sample with good optical clarity and 1 to 3 mm thick was to be expected.

2.2 Properties of the Polymer Hosts

A brief series of simple tests were performed on samples of PS, PMMA, and PVA (already polymerized) purchased from chemical suppliers.

1. It was quickly determined that PS will melt easily at 150 C and can be readily handled and cast into a number of shapes. Heating in air produced a modest odor and also resulted in a faint yellowing of the polymer (this was indicated to be likely from comments found in the literature [5]). In the future, we may choose to melt the polymer under a nitrogen atmosphere.
2. PMMA would not melt, but would tend to decompose and rapidly vaporize (rather cleanly but with an unpleasant odor). It was clear that the simple melting procedure used for PS could not be used here, but that direct polymerization of methyl methacrylate (MMA) would be required.
3. PVA would not melt, and on decomposition would form a tan to black residue which was rather unattractive.

All the above polymers would readily dissolve in the right solvents, but it generally required a fair amount of solvent to produce a solution of modest viscosity. The eventual goal was to produce a relatively thick sample, free of solvent, so removal of the solvent was quickly seen as a problem. Attempts to drive off the solvent from samples a few mm thick lead to severe bubbling which results in samples having unacceptable optical quality. Based upon our need for relatively thick samples, it was quickly determined that the samples must be either melted and cast (as in the case of PS), or directly polymerized into the shapes desired. It was also found, that once polymerized, both PS and PMMA provided samples which could be easily cut and polished to a quality suitable for our needs. In the case of PS, an alternative method for preparing an optically clean surface was to rapidly melt the surface of the sample while pressing it on a heated glass slide. Upon cooling, the glass slide is easily removed to provide a very clean, smooth flat surface.

Based on the above considerations, it was concluded that attention should be directed to the melting and casting of PS and direct polymerization of MMA.

2.2.1 Free Radical Polymerization

The polymerization of styrene and MMA is quite simple with the only negative aspect being the odors generated. These materials are of modest volatility and should only be handled in a ventilated room. The principal means for polymerization of these two materials is via free radical mechanisms. The free radicals can be readily provided by chemical additives called "initiators". The free radicals are generally provided by the breakdown of the initiator molecules.[6] This breakdown can be driven thermally (as in the case of benzoyl peroxide) or via UV illumination (as in the case of benzoin). Once the free radicals are generated, they become the "seeds" for creating long polymer chains. When the free radical adds to the monomer molecule, the new molecule retains the reactive capacity to add to more monomers (see Figure 3). This process continues until the radical couples to another radical, ending the chain. Via this chain growth

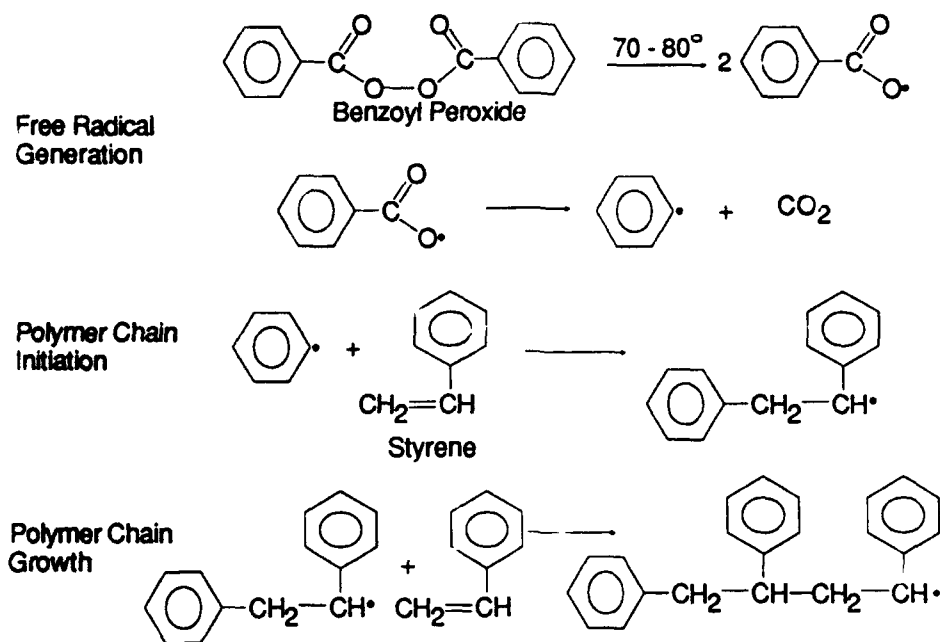


Figure 3. This is an example of the free radical polymerization of styrene which is initiated by the thermal decomposition of benzoyl peroxide. Once the polymer chain growth has been initiated, it can continue until one of several chain termination events occurs.

mechanism, a rather small amount of initiator (0.5 percent or less) is all that is required to provide full polymerization.

2.2.2 Polymerization of MMA Using Benzoyl Peroxide

Benzoyl peroxide readily decomposes at 70 to 80 C to form the necessary free radicals. It is readily soluble in MMA. Our procedure for preparation generally involved placing the MMA/benzoyl peroxide solution in an aluminum weighing dish, which is then placed in a glass petri dish (with cover). Upon heating to 80 C in an oven, polymerization began in about 1 hour, and was fairly complete in 2 hours. Care needs to be exercised in not trying to polymerize a sample which is too thick because thick samples can bubble severely. Bubbling can be a problem during the polymerization process because the polymerization reaction is quite exothermic. In principle this could be handled by attempting to control the temperature, however, this is quite difficult. The cause has been suggested in the literature [7] to be related to the steric hindrance provided by increased viscosity. It is believed that when the MMA is approximately 40 percent polymerized, molecular motions become adequately inhibited so that ending of the chain reaction via the combination of two radical chains becomes unlikely. The chains then continue to grow rapidly, and the exothermic reaction has been reported to be explosive in certain cases.

We have found that this problem can be adequately avoided by polymerizing samples which are only 2 to 3 mm thick at a time. After polymerization (with some loss of MMA due to vaporization) one can obtain samples 1 to 2 mm thick. Successive layers of PMMA can be easily built up by adding more solution, and a sample of 1 cm thickness can be obtained with a few hours more work.

The general optical quality is good, although the total absence of bubbles and uniformity of thickness is achieved when the amount of care taken is increased.

2.2.3 Polymerization Using Benzoin

A commonly used alternative to the initiation being driven thermally is to use a photoinitiation process. This has the advantage of permitting one to carry out the polymerization at a lower temperature. The lower temperature is an advantage because of the reduced odor problem, a reduced MMA loss due to vaporization, and a reduced problem associated with the bubbling caused by the runaway exothermic reaction.

A typical procedure involves preparing a solution of MMA and benzoin (0.5 percent). The solution is again put in an aluminum weighing dish and inside a glass petri dish (with cover). A low power UV lamp is then placed over the sample. The initial increase in viscosity takes 3 to 6 hours and complete polymerization takes 6 to 18 hours. While being a slower process it also seems to be a much lower temperature process. The heating by the lamp does not raise the sample temperature above 40 C. Samples 5 to 6 mm thick can be obtained in a single step which are of high optical quality and completely free of bubbles. (Some bubbling was noted for a sample 1 cm thick.) With the modest number of samples prepared so far, it can be surmised that the sample quality provided by the UV photoinitiation procedure is higher and less work is involved.

2.3 Adding the SHB Species

Several considerations are of importance in introducing the SHB molecules. First is the relatively limited solubility of these materials. This has proved to not be a problem, since the optical density obtained is adequately high due to the high molecular absorption cross section. Another factor for consideration is that the best results in terms of the performance of the SHB materials could be expected if the use of solvents is either completely avoided or at least minimized.[4] Therefore, direct dissolution in the polymerized material or monomer is desired.

2.3.1 Polystyrene Samples

In the case of the materials selected for examination, all, except for H_2Ch-e_6 , were directly soluble in polystyrene. This approach to preparation was tedious, but did not involve an intervening solvent. In each case, the solubility limit seemed to coincide with the absorption reaching an optical density of about 1 in a 1 cm thickness. Dissolution was carried out by simply weighing out a few milligrams of the SHB species and stirring it into a melted sample of polystyrene. Repeated patient heating and stirring was required to achieve complete dissolution, and dilution through the addition of more polystyrene was often required to finally eliminate all the visible solid porphyrin material. It became clear that diffusion of the SHB molecules through the PS was an important process to enhance the dissolution, and it appeared that the H_2P had the most rapid dissolution, while the H_2Ch-e_6 appeared to be soluble, but was not able to diffuse rapidly. All the others appeared to be amenable to this rather direct method for introduction into the PS.

The problem with H_2Ch-e_6 was overcome by initial dissolution of the material in 1 ml of dimethylformamide. This solution could then be added directly to a large amount of polystyrene to provide appropriate dilution. This procedure provides samples with good clarity and uniformity and with an absence of particulates.

Realizing that prior dissolution in a small amount of solvent could eliminate the particulate issue, we found that H₂Ch-I was readily soluble in a few drops of dichloromethane which could then be added to the polystyrene. Upon melting of the polystyrene, most of the solvent vaporized and the H₂Ch-I readily dissolved in the PS providing samples with excellent optical clarity and quite high optical densities if desired. We therefore concluded that the use of a small amount of solvent was required.

2.3.2 Polymethyl Methacrylate Samples

As was stated above, the preparation of the PMMA samples was not possible by simple melting of the polymer, and the preparation of thick samples, free of solvent, from solution could be tedious. The principal path of interest then lies in the direct polymerization of the MMA solution which contains the SHB material. It was found that this approach does not permit all porphyrin compounds to be used in such a procedure.

The limitation was found to be caused by the attack of the free radicals on some of the porphyrin compounds. If the porphyrin ring is broken by free radical addition, the dye becomes effectively bleached. It was found that this process could be avoided by proper selection of the chemical groups added to the central porphyrin ring and their exact locations. The reasoning behind why this happens is presented in the discussion which follows.

2.3.2.1 Free Radical Addition of MMA

MMA undergoes addition across the double bond between two carbon atoms. Such an addition can occur across any unsaturated bond (in principle), however, unsaturated bonds which are highly stabilized due to resonance effects (as in benzene) may not be appreciably attacked. A simple example of this is styrene which undergoes free radical addition across the lone C-C double bond (to form polystyrene), but attack does not occur on the accompanying phenyl group (see Figure 3).

In the case of the porphyrin ring compounds one may expect that free radical attack may be more probable at certain locations on the exterior carbon atoms of the central ring. If additional chemical groups can be added to the carbon atoms most available for attack, we find that bleaching of the SHB species is now inhibited. A strong suggestion that this was possible was made by several Japanese references.[8,9,10] In particular these references indicate that direct polymerization of MMA and related monomers is possible without bleaching of the porphyrin compound if the porphyrin ring is surrounded by phenyl groups attached at locations 5, 10, 15, and 20 on the porphyrin ring (see Figure 2) as in the case of tetraphenyl porphine (TPP). It is believed that these phenyl groups provide hindrance to the attack of free radicals simply due to their physical size. There is also an indication from the literature that the added phenyl groups are not restrained in their orientations relative to the central porphyrin ring, rather, they are able to rotate freely in solution.

The exact location of the additional groups at locations 5, 10, 15, and 20 also seems to be important. By comparison, we determined experimentally that ethyl groups added to locations 2, 3, 7, 8, 13, 14, 18, and 19 (as in the case of octaethyl porphine) did not provide any significant protection against free radical attack because this compound was found to readily bleach under polymerizing conditions.

The problem of bleaching was also shown to not be simply due to the presence of the initiator, since a solution of porphine in MMA (without any initiator added) bleached in a few hours without any noticeable polymerization taking place.

It would appear that unless the porphyrin ring is stabilized by the protection of locations 5, 10, 15, and 20, the introduction of these materials into polymers cannot be carried out under conditions where free radical polymerization is possible. This turns out, however, to not be a severe restriction because of the large number of related compounds which are still available for use. It should also be noted that the key aspect which distinguishes the chlorin derivatives from the porphine derivatives lies in the saturation of the bond between locations 2 and 3. Since these locations do not seem to be key to preventing free radical attack, we can expect that the chlorin derivatives of the tetraphenyl porphines are also stable against bleaching during polymerization.

2.3.2.2 Experimental Successes with PMMA

The conditions under which PMMA could be directly polymerized and not cause bleaching of the SHB material were not studied extensively because it was not warranted under this program. The results, however, were deemed to be very encouraging in that all samples necessary for carrying out this program were shown to be easily prepared and a clear path exists for future preparations of materials of higher performance (homogeneous linewidths smaller than 1 GHz).

It was shown that TPP doped samples of PMMA could be readily prepared as thick slabs (3 to 10 mm thick) via direct polymerization. It was demonstrated that no noticeable bleaching occurred whether the initiation process was driven thermally using benzoyl peroxide or via UV light using benzoin. Both procedures worked well, with the benzoin providing samples of somewhat better optical quality. The success of the benzoin was somewhat surprising because of the strongly absorptive properties of the TPP itself in the UV. We were concerned that the TPP might prevent sufficient light from reaching the benzoin initiator molecules and prevent efficient polymerization. It would appear that this is not a problem, and that the TPP is very stable under these long term UV exposure conditions. (The success of photoinitiated polymerization also turns out to be strong evidence supporting the contention that the SHB medium will **not** be sensitive to irreversible photobleaching. One can therefore expect that these materials will permit a long product life.)

A simple test was performed using crossed polarizers which indicated that the PMMA samples prepared were quite stress free. Similar tests of the PS samples indicated that stress free material could also be prepared if care was taken to cool the samples slowly and in a container which was of adequate flexibility. Since stress birefringence is common in many polymers, this can be a source of concern. If the stress birefringence is severe enough it can lead to an optical distortion effect, however, this level of stress is easily avoided. Under more modest stress levels, the polarization properties of the material can reduce the efficiency with which holograms are created (more molecules must be bleached to generate each hologram). Since essentially stress free samples could be easily prepared, neither problem is anticipated to be of significant long term concern.

2.4 Indications of Future Materials Development Paths

For the preparation of uniform thick samples of doped polymers having arbitrary composition, direct polymerization would appear to represent the most clear path to obtaining high quality samples. This approach is favored in the long term because while PS can be easily melted and mixed with many SHB materials, the smallest homogeneous linewidths have been reported for polyethylene (PE) and copolymers of ethylene and MMA.[4,3] Also, while PMMA is optically very clear, PE is generally translucent. This translucence is the result of the tendency of PE to form polymer crystals upon cooling which scatter light. Very rapid quenching of melted samples can inhibit this process somewhat, but the long term stability of such a sample may be in doubt.

The interest in the performance of PE is caused by the observation that when used as a host material for the SHB species it provides the most narrow homogeneous linewidth observed among the organic SHB media. In general the homogeneous linewidths of porphyrin dopants in PMMA or PS are roughly 20 times larger than that observed for the same materials in PE. The solution to this divergence between optical clarity and homogeneous linewidth is provided by Japanese workers [3] who have shown that the observed homogeneous linewidth is linearly related to the ratio of components used in preparing copolymers of ethylene and MMA. Their experimental results are plotted as a function of number of carbon atoms in the alkyl chains in Figure 4 and indicates the ability to prepare copolymer samples of virtually any copolymer ratio in an attempt to obtain the homogeneous linewidth desired. One would also expect that at some well defined copolymer ratio the samples will be of adequate optical clarity for our purposes. This expectation is based on the realization that one simply needs to prepare copolymers where the local structure is adequately irregular to prevent crystallization. This can be provided by the preparation of ethylene/MMA copolymers or by the polymerization of alkyl methacrylate copolymers where the alkyl groups are rather long (see Figure 5). In both cases one find that the homogeneous linewidth approaches that found in PE.

The selection of the porphyrin compound determines the wavelength range over which hologram recording can be accomplished. H_2P (the simplest of the porphine derivatives) absorbs with its 0-0 vibrational band at 611 nm. H_2Ch (the chlorin analog) has a very well defined strong absorption at 635 nm. In general, for every porphine derivative, there is a matching chlorin derivative. The absorption wavelength of the chlorin derivative is generally located 25 nm longer in wavelength. The addition of chemical groups at any location in the porphyrin ring system generally increases the absorption wavelength. For example, TPP has an absorption peak at 647 nm, while octaethyl porphine absorbs at 618 nm.

The addition of chemical groups at locations 5, 10, 15, and 20 on the porphyrin ring does not seem to be a factor which significantly restricts the material selection process. In fact, the process for preparing these porphine derivatives is easier than that for preparing the basic porphine material itself. This process ease differential is reflected in the significantly lower prices on the porphyrin derivatives (\$10/gram) having several additional chemical groups compared with the simple H_2P and H_2Ch compounds which are far more expensive (\$100/milligram). Introducing modifications to the phenyl side groups alters the absorption peaks further. For example, tetrakis(pentafluorophenyl) porphine absorbs at 659 nm, while tetrasodium tetra(sulfonatophenyl) porphine absorbs at 640 nm. As we can see, the modest requirement that phenyl groups be attached to the porphyrin ring at specific locations is not a serious limit, since a range of SHB species are available and all those mentioned above have been reported in the literature as SHB recording media.

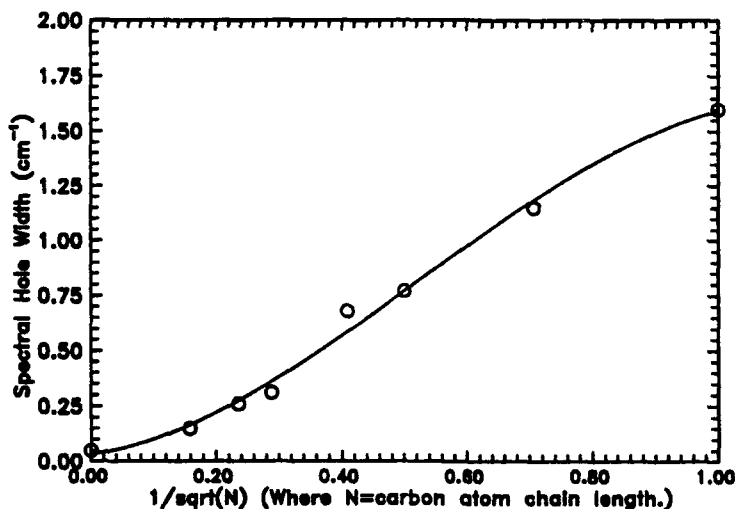


Figure 4. Spectral hole width for 1,4-dihydroxy-9,10-anthraquinone in various polymer host matrices. (This material was selected as representative of SHB media in general.) Note the simple correlation between hole width and polymer composition.

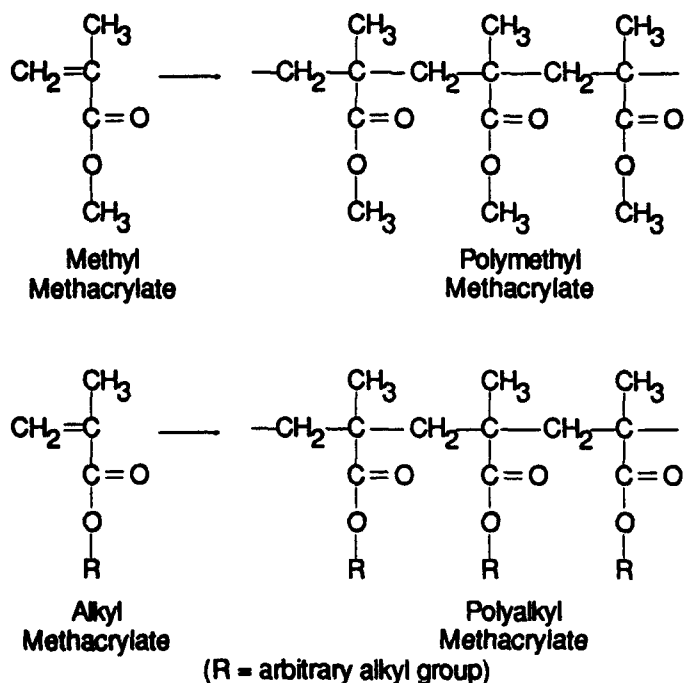


Figure 5. This diagram shows how free radical addition across the C-C double bond in MMA permits polymer chain growth. By simple substitution of any number of selected alkyl groups for the methyl groups present one can alter the alkyl content of the polymer and thereby control the homogeneous linewidth.

The same variety of compounds exists for the analogous chlorin derivatives with the same trend in peak wavelengths. An advantage to the chlorin analogs is that the spectra are generally simpler in general structure, with each compound having only a single strong absorption peak in the red or near IR corresponding to the 0-0 vibrational band. This presents an advantage when considering the potential use of a number of photochemical species in the same polymer, for the spectra will not strongly overlap and interfere with each other. By contrast, the spectral structure of the porphines can be far more irregular, with several shorter wavelength peaks having strong absorptions which are not well spaced from the principal long wavelength absorption.[11] All things considered, the chlorin derivatives which also contain the chemical structure inhibiting free radical attack should be rather easy to obtain and simple to introduce into polymers, providing the desired spectral properties.

In the long term, an extra concern for data longevity must be added to the SHB material requirements. This has been identified as having a straightforward solution through the use of deuterated host materials.[12] By replacing the hydrogen with deuterium in the host medium, the data life can be extended from weeks to thousands of years. Given the ready availability of deuterated organic chemicals, and the relatively small quantities of polymer host material actually required for each computer system, this should not be a significant technical or cost factor for the future.

2.5 Summary of Media Preparation

The materials preparation carried out so far has been very successful. Simple procedures have been worked out which provide polystyrene samples of high optical quality out of polystyrene. It has shown that all of the porphyrin compounds examined are readily compatible with our polystyrene preparation method which is a simple melting and casting process.

When the preparation of PMMA or other copolymer mixtures is desired, direct polymerization via free radical initiation is the preferred method of preparation. UV photoinitiated polymerization seems to be the superior method using simple procedures. The polymerization process indicates that a specific class of porphyrin derivatives should be used in order to minimize bleaching through free radical attack.

It must also be remembered that the free radical initiation mechanism is only one of several major approaches available for the preparation of polymers. The specifics for the free radical polymerization of MMA and styrene have been presented and used in this program only as examples. While the results obtained are excellent, the capability to provide SHB material via numerous alternative approaches also exists.

Based on the wide range of porphyrin compounds available, the range of literature information available, and the general flexibility inherent in the ability and ease with which polymers can be prepared, a clear path can be seen to the preparation of SHB materials for both modest and high performance requirements.

3 Optical System Assembly

The optical system design has followed very closely the design initially outlined in the SBIR Phase I report and proposal. The details provided in those documents will not be reiterated here. The general optical layout is shown in Figure 6 and should be compared with the schematic diagram of the system seen in Section 2. The principal features of the system which have been refined are;

1. the tunable laser system,
2. the camera selection, and
3. the LCD selection.

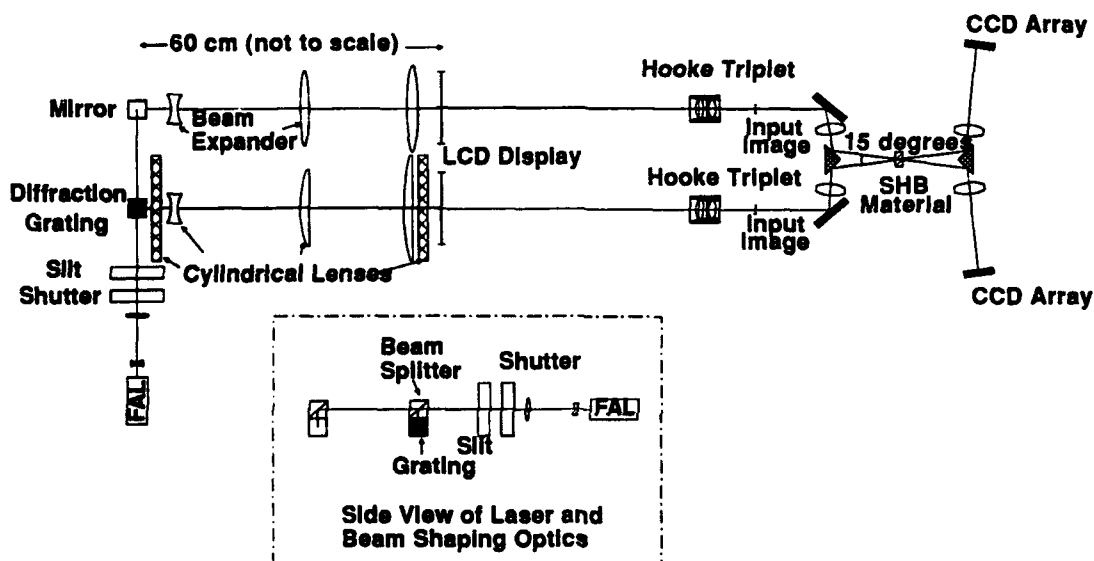


Figure 6. Detailed layout of the optical system which has been assembled. With the exception of the LCDs the key components have not been significantly altered from the originally proposed design.

3.1 The Tunable Laser System

The requirements on the tunable laser are that it provide a set of 64 equally spaced wavelengths which can be accessed via computer control. It would be desirable to have several mW of power at least and the laser linewidth should be comparable to the homogeneous linewidth of the SHB medium selected. Tuning rate need only permit scans of the laser wavelengths in seconds, as opposed to minutes or milliseconds. Finally, the tuning must be repeatable over the duration of our experiments (hours).

It had originally been suggested that this program would utilize a Frequency Agile Laser (FAL) which was electro-optically tunable and readily available at SPARTA as our laser source for the Neural Network Optical System. However, our analysis of our performance needs indicated that a more correct choice would be a tunable dye laser system which is tunable through the use

of a mechanically adjustable birefringent filter (BRF). While the dye laser based FAL system could provide excellent speed in terms of wavelength random access, we found that the laser linewidth was limited to the many gigahertz range.

The advantage of the BRF tuner was that it provided a fundamentally narrower laser line as well as having fewer losses. The lower loss level provided us the ability to introduce etalons as additional tuning and line-narrowing elements. Our composite dye laser design made use of a BRF tuner, a 0.5 mm thick etalon and a 10 mm thick etalon. The composite performance resulted in a laser linewidth of roughly 0.3 GHz. Moreover, by simple rotation of the BRF tuner one could change wavelength by approximately 300 GHz increments. Over a wide range (20 nm) we could achieve a suitably constant laser line width at a set of wavelengths. These wavelengths are well defined and well-spaced, providing the incremental illumination which is required for the neural network. Over a 20 nm tuning range we estimate there to be roughly 64 independent wavelengths available for tuning.

In our tests of hologram recording (to be discussed later in this section) we have found that chlorin doped polystyrene provides a range of operation of approximately 10 nm. This automatically provides us with 32 independently addressable wavelengths. To achieve 64 wavelengths we have two principal options:

- 1) add a second dopant to the polystyrene, increasing the absorption band width to roughly 20 nm, or
- 2) tilt the etalons so as to provide a second set of laser wavelengths which are shifted relative to the first, thereby providing two sets of 32 wavelengths within the same 10 nm tuning band.

Which of these two options we shall utilize is still to be decided.

The turning of the birefringent filter is provided by an Oriel "Encoder Mike" which is a motor driven micrometer system which is computer controllable through a standard RS-232 port from a PC. This micrometer provides adequate precision for reliable "hopping" between laser lines in a repeatable manner. A modest amount of care must be exercised for positioning of the BRF tuner to avoid laser emission at two laser lines simultaneously, however, this is easily accomplished through positioning precision on the level of one percent.

3.2 Camera Selection

Early in the program, it was found that a CCD camera manufactured by Electrim Inc., was of a format, size and performance quite ideal for our applications. This thermo-electrically cooled camera has a modest pixel format (165 by 192) which matches well our proposed goals of 64 by 64 pixels. The camera image is automatically digitized to 8 bits and read directly into PC memory. This conveniently places the camera image directly at the disposal of any high level programs for further analysis of the image and extraction of digital data from the holographic images. The software to control the cameras is available as C linkable routines which can be readily incorporated in the overall system software. Furthermore, multiple cameras can be operated from the same PC and are completely software selectable and controllable in all the critical control attributes.

3.3 LCD selection

The selection of the Liquid Crystal Display (LCD) has proved to be a key item in terms of data format, image quality and convenient match with the cameras. Our experience in a previous holographic memory program has shown that commercially available LCDs are quite compatible with the requirements of our demonstration system, however the performance was only marginal when considered in terms of image contrast. The LCD which had been used in the previous program was not an active matrix display, therefore it suffered from two problems associated with contrast. First, the contrast was limited to roughly 20:1, which we found to cause a noticeable loss in visible image quality. We believe that the active matrix arrays, which boast a contrast of 100:1, should enhance image quality and reduce noise in the resultant recorded digital data. Second, the array we had previously selected demonstrated a "shadowing" problem which adversely affected image resolution. This shadowing problem was apparent to the naked eye when a single pixel was turned "ON". The adjacent pixel, which was addressed by the LCD sequentially, became partially turned on, resulting in a shadowing effect. The net result was to reduce the effective resolution of the LCD in one dimension by a factor of two. We believe that an active matrix LCD should provide better performance on these two points because of the greater independence of the transistorized nature of each pixel.

With the requirement added that the LCD be an active matrix one, the composite requirements of the LCD can be summarized as:

1. active matrix (for greater contrast)
2. black and white with gray scale (a color LCD pixel is usually composed of 3 adjacent LCD pixels with integrally incorporated color filters which would cause significant light loss in our application),
3. readily addressable through a commonly available PC video interface (although even composite video could be adequate for our needs),
4. LCD must be able to be illuminated transmissively, and
5. the pixel dimensions (aspect ratio) should permit a good match with the cameras selected.

The composite of these requirements is well met by the performance of several liquid crystal projector systems from Sharp and GE. The systems we are presently considering include the XG-1100U, XG-1000, and the XG-2000 from Sharp or the LCD10 from GE. All these systems have a similar general construction in that they all utilize 3 separate LCD screens, the black and white images from each being coupled to produce the full color images. (Each LCD is transmissively illuminated with chromatically filtered light, and then the three primary color images are recombined as a single optical image.) They all provide the computer interface required, and are high contrast active matrix systems. An extra benefit is that a single projector system provides 3 separate LCD screens of excellent quality, a factor which actually makes the systems quite a cost effective choice. We are examining each of these systems in detail in order to determine the best match to the CCD cameras.

At present, the optical system is fully assembled, complete with tunable laser and cameras, and is in the basic configuration which should permit insertion of the LCDs.

4 Holographic Test Results

During the optical system testing as well as the material preparation there have been a number of holographic tests which have been performed to indicate performance with respect to a number of parameters. Since the material properties are generally known through the available literature, our results could be readily compared to verify whether our optical and cryogenic systems as well as the material were performing as anticipated.

4.1 SHB Medium Cooling

The holographic tests performed verified that the spectral hole burning medium selected (Chlorin-I in polystyrene) was performing as anticipated. It was generally observed that the preparation of the material required some care on a few important items in order to provide the best possible image quality. We identified three key items as:

1. care must be exercised to prepare the material under circumstances which are free of any particulate matter including dust and insoluble residues,
2. the host polymer must be cast into the proper shape required for the cryogenic system, however this must be accomplished in a manner which induces no residually stresses or non-uniformities in the material, and
3. because the host polymers (polystyrene in particular) are stress birefringent, the samples must be held in the cryostat in a manner which applies minimal force to the sample, however good thermal contact to the sample must be maintained to keep the material at cryogenic temperatures.

The first two items above are simply a matter of adopting suitable procedures for sample preparation the details of which are not particularly interesting so they will not be discussed in detail here. The third item (stress free thermal contact in the cryostat) has provided us with some cause for concern, but an excellent solution was adopted which has positive short term and long term ramifications.

The cryostat which we had purchased for this project was a compact "Supertran" cryostat manufactured by Janis Research. This cryostat was selected because of its low cost as well as the fact that the basic structure of the "cold finger" resembled that of the commercially available refrigerator systems. Inherent in the design is the concept that the sample of interest is cooled conductively by mechanically making good thermal contact to the sample. We found that this approach caused serious optical distortions of the recorded images and our measurements suggested that the sample temperature was not at the low temperature of the sample holder.

A common alternative approach to sample cooling at these temperatures (particularly for samples which conduct heat poorly) is to surround them in a helium atmosphere, which is highly thermally conductive. This approach generally uses the same helium supply to provide total cooling as well as thermal contact. Unfortunately we saw this approach as a long term limitation when considering the use of a closed cycle refrigeration system. Our solution to this issue was to fabricate a sample holder which incorporated a static helium atmosphere surrounding the sample while the primary cooling is provided via mechanical contact to the cold finger assembly (see Figure 7). This sample holder provides excellent thermal contact to the polystyrene sample. Optical transmission is permitted via the sapphire windows, and the flexible vacuum seals are of indium metal. Thermal conduction leakage to the sample holder via the helium gas tubing is

minimized by making the tubing of stainless steel. While this design permitted us to avoid the obvious extra expense of purchasing a new cryostat, it also proved out a sample holder design which can easily be engineered to be compatible with a closed cycle cryostat system.

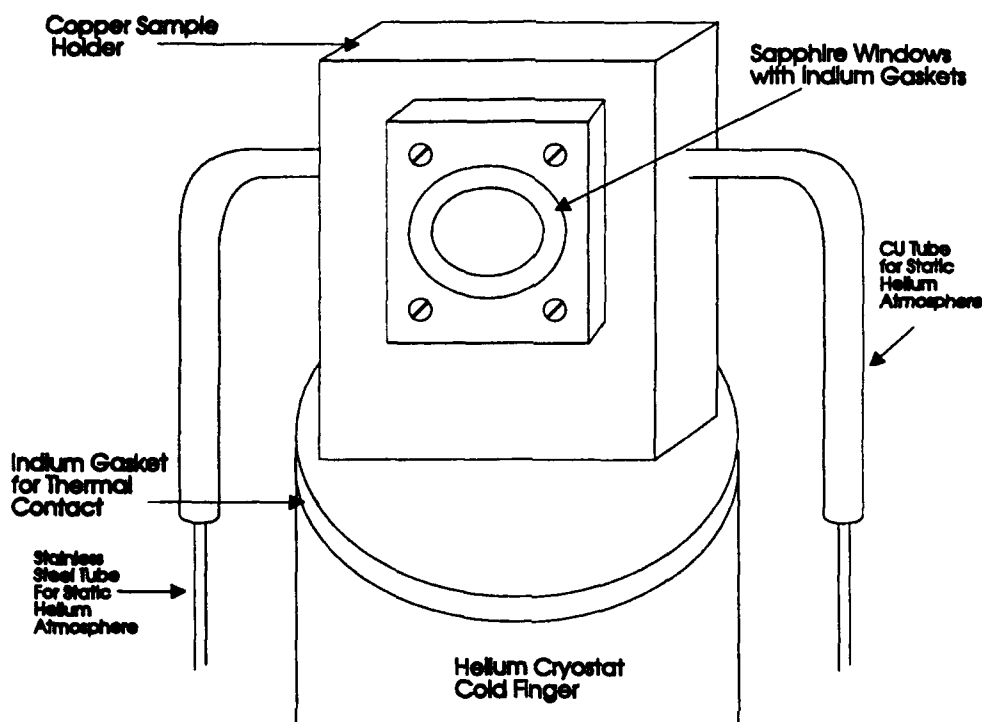


Figure 7. Diagram of the sample holder design which permits a static helium atmosphere for stress-free thermal contact to the SHB medium. The cooling is provided conductively via mechanical mounting of the sample holder to the cold finger of the cryostat.

4.2 Standard Holographic Tests

Fundamental to the operation of the neural network system must be the ability to record and read out high resolution holograms from both input planes. Furthermore, we are required to demonstrate that both angle multiplexing and wavelength multiplexing are readily possible utilizing our system design. We have successfully confirmed these capabilities. These tests are carried out by placing a chrome mask of the Air Force resolution chart in the 2D image plane (see Figures 8 and 9). To create a suitable reference beam, a slit was inserted in the chromatically steered leg of the system which, because the illumination is brought to focus as a single line, causes the illumination to be reduced to that of a single point. The light from that single diffraction-limited point then uniformly illuminates the SHB medium for proper interference with image containing beam. Lenses and cameras are placed in the beams after the light traverses the SHB medium, and the images and holograms can be viewed directly via the CCD cameras.

Typical results are shown in the figures which follow. These CCD camera images are comparisons of the input images and the holographically retrieved images as viewed by each of

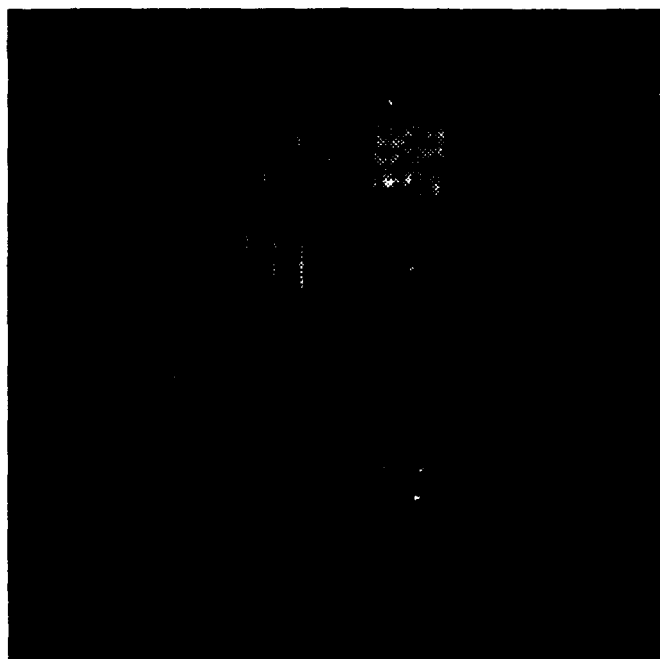


Figure 8. Input image of the Air Force resolution target on a chrome mask used to test the resolution of the optical system and the CCD cameras.

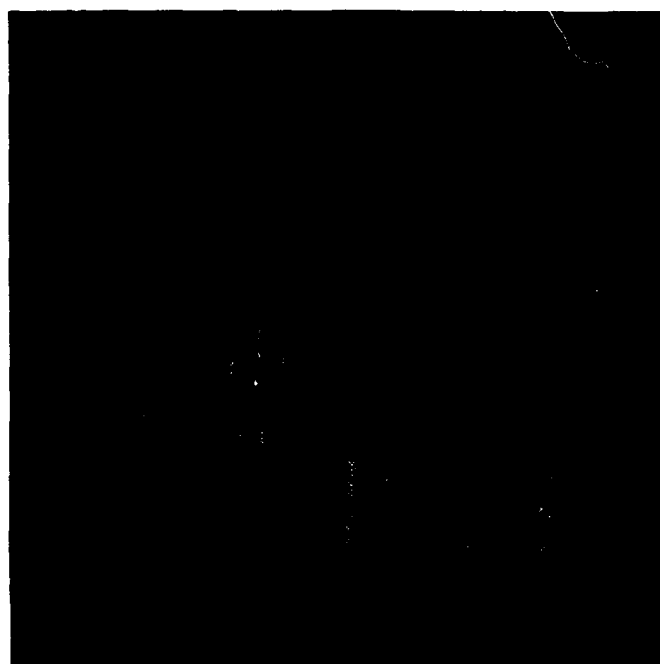


Figure 9. Recorded hologram of the Air Force resolution target. Note that the resolution of the image is principally limited by the CCD camera and the minor imaging imperfections can be traced to imperfections (dirt) on the optical components.

the CCD cameras. Holograms from both legs can be viewed from a single recorded pattern. As can be seen from the images viewed below, the input and output resolution is nearly identical. The approximate hologram efficiency observed was roughly 10^{-3} and the exposures required to create these holograms closely match our estimates based on literature reports of material properties. Some background scatter is seen in the holograms which we attribute principally to residual particulate matter in the polystyrene sample and accumulated dust on some of the optical components. We believe that a modest increase in the care of sample preparation and a cleaning of the optical elements will provide even clearer holographic images.

Simple tests were also performed which showed that both angle multiplexing and wavelength multiplexing is readily possible for the recording of multiple holograms. This capability was clearly demonstrated by angle multiplexing 3 holograms, and wavelength multiplexing 10 holograms simultaneously with no apparent crosstalk. The separation in angle and wavelength matched our theoretical and design requirements very precisely. This cursory test was not at all limited by system performance but only by experimental convenience. More demanding tests shall be performed when the system is properly brought under computer control.

4.3 Holographic Tests Verifying Connectivity

The fundamental requirement of the neural network system which sets it apart from a typical holographic system is the ability to relate or "connect" any point (or group of points) in one input plane to any point (or group of points) in the other input plane. The "connectivity" provides the fundamental attribute which is key to the operation of the neural network system. To this end, we have performed a few simple tests which verify this attribute in the fundamental sense.

While the 2D image plane is fully illuminated under standard operation, the chromatically steered image plane is typically illuminated by a full line (as opposed to the single point used in the simple tests discussed above) when considering a single wavelength. To test the ability to connect these illuminated patterns, we placed a simple contrast pattern of equally spaced lines across the line illumination in the chromatic leg (resulting in a linear array of dots) and retained the resolution target image in the 2D image leg. After a short holographic exposure we were able to verify that the linear array of dots could be faithfully retrieved (see Figure 10) when the 2D image plane was illuminated with the resolution target.

Further tests indicated similar connectivity when the array of dots was further patterned. Other tests were also performed which showed that large area features in the 2D plane could be appropriately connected to the linear pattern on the chromatic leg. At present the resolution of these features which provides faithful connectivity is somewhat limited. The complete high resolution connectivity is anticipated to improve markedly when the liquid crystal displays are inserted and the system is made fully functional under computer control.

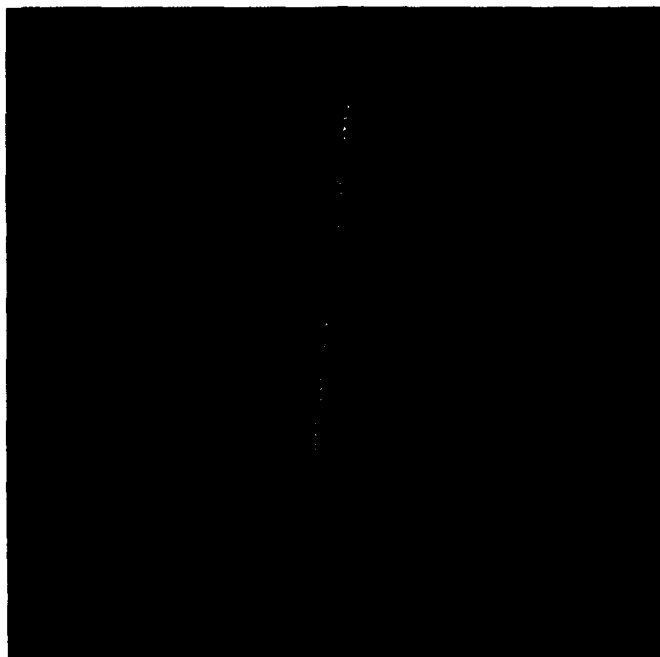


Figure 10. Holographic image of the linear array of dots corresponding to the chromatically steered image plane. This holographic image is identical to the input image. Similar images representing more complex patterns have also been faithfully retrieved under identical conditions.

5 A 4D Neural Network Demonstration

5.1 Introduction

At the halfway point of this program, we have the optical train essentially complete and have demonstrated the recording of holograms in dye-doped organic polymer host material. We have yet to insert the spatial light modulator(s) into each leg of the optical setup, but this will be a relatively simple extension of the software developed for a previous program. Currently, we have spent little time developing the software to run the neural network. Most of the second part of this program will be devoted to electronics and neural network operation.

We need to plan the demonstrations before the 4D NN system is complete. The series of demonstrations will lead us through the implementation of the electronics and system operation in an incremental fashion, in much the same way that the optical train was constructed incrementally.

In the neural network area, we had no specific demonstrations of applications planned at the start of the program. In large part, this decision was made because of the level of funding, which is insufficient to both build the system and train it to accomplish a specific task. The size of our planned network was an important factor in this decision. A small network can be trained in a short time, but training an extremely large network is a much bigger task. Instead, we planned to demonstrate the operational capability of the system with some simple demonstrations.

As a result of attending a recent neural network applications conference,[13] we have identified a number of applications which could benefit from the use of an extremely large network. These applications include passive sonar signal processing, ship wake detection from SAR (synthetic aperture radar) data, automatic target recognition, and perhaps control of complex processes. In each of these areas, conference speakers discussed *ad hoc* approaches to the problem, in an attempt to solve the problem with the much smaller number of neurons available to them through electronic hardware or computer simulation. Until these approaches have either succeeded or have been proven to be very limited because of the small number of neurons, none of these approaches can be used to motivate a *requirement* for extremely large networks.

Several applications which may require a very large neural network include a type of traveling salesman problem and a large associative memory. In the traveling salesman problem, for example, a terrain map, perhaps including hazards such as radar installations or anti-aircraft batteries, could be stored in the neural network, which would solve for the safest trajectory for a given type of aircraft to fly, in real time. The amount of data to store in the network would almost certainly require a very large number of interconnects. This application is probably too difficult to demonstrate, even in a simple way, during our program. An associative memory is another architecture for which a very large network is definitely required. One advantage of associative memory is that parallel search techniques can be used, however, this function is difficult to implement electronically.[14] In our optical implementation, parallel search can be performed on a very large data base. In addition, associative memories can be used to solve many problems, so their utility is established. (For example, an associative memory could solve the sonar signal understanding problem and the automatic target recognition problem.) In the remainder of this section, we will discuss a series of demos which illustrate associative memory operation in a very simple fashion.

5.2 Objectives of the Demonstration(s)

Our demonstrations will begin with the simple optical properties of the 4D connection medium, and will progress to demonstrations showing the combination of the optical and electronic capabilities of a complete neural network.

We have already demonstrated the recording and playback of holograms in an SHB medium. The next step is to record a hologram of one 2D pattern using a second 2D pattern as a reference. This hologram would essentially be an association of two patterns, one presented to the input plane and one presented to the training plane. (Either the input plane or the training plane can be chosen to be the wavelength-coded plane for convenience, since the network will ultimately be used in "symmetric" fashion as discussed below.)

The second optical demonstration will show that there is no crosstalk between connections in the wavelength coded direction. (Crosstalk in the Bragg direction is already suppressed by 3D volume recording.) We can show this by presenting the same input pattern to the neural network, slightly shifted in the wavelength-coded direction, showing that no output results. (If the connections were space-invariant, the training pattern in the first recorded pair would appear shifted in the output plane by the same amount as the shift of the input pattern.

A third experiment would involve teaching the 4D network a second pair of patterns to associate. The pattern presented to the input plane would be a shifted version of the input used in the first experiment, and the pattern to be presented to the training plane would be an entirely different pattern from that used in the first experiment.

A better understanding of the advantages of the 4D interconnect network can be obtained by studying the performance of a 3D system for the same inputs. Studying a 3D system can be achieved fairly simply by placing a small number of lenses in the chromatic leg of the 4D neural network optical system and working with a single color. We believe that the response of a 3D interconnect network to the pairs of patterns discussed above would exhibit severe crosstalk, with overlapping versions of the two training plane inputs in response to a single pattern presented to the input plane. In other words, the connections established by the first pair of patterns connect many more states in the input and output planes than intended, and so not all the states in the input and output planes can be used.

Finally, our goal by the end of the program is to show that we have constructed a working 4D neural network. Originally we planned to implement a demonstration of a multilayer network which could learn associations using the backpropagation algorithm. Backpropagation, however, requires very long training times (or a large training set) which might be beyond the scope of our current program to implement in a convincing fashion. The bidirectional associative memory (BAM) architecture[15], which can be implemented using a combination of optics and electronics in much the same configuration as backpropagation, appears to be ideally-suited for demonstration of our 4D optical neural network.

Following Kosko[15], we can describe the operation of a BAM as follows. Assume we have an input vector A and an output vector B associated with it. These can be stored in a memory as a pair (A_i, B_i) ; in an autoassociative memory, $A_i = B_i$, while in a heteroassociative memory the two vectors are not equal. In this case, associative recall is simply vector multiplication, $B = AM$, where M is the outer product of the two associated vectors,

$$M = A_1^T B_1 + A_2^T B_2 + \dots + A_f^T B_f.$$

The matrix M can be created optically by recording a hologram with A as the object beam and B as the reference beam.[16] The vector B can be reconstructed by illuminating the hologram with the input vector A . (In our case, the vectors A and B are two-dimensional, and the matrix M is four-dimensional, but these forms can be used to represent the lower dimensional quantities in Kosko's paper.)

The bidirectional operation of the memory is illustrated by the following set of equations.

$$\begin{aligned}
 A &\rightarrow M \rightarrow B, \\
 A' &\leftarrow M^T \leftarrow B, \\
 A' &\rightarrow M \rightarrow B', \\
 A'' &\leftarrow M^T \leftarrow B', \\
 &\vdots \\
 A_f &\rightarrow M \rightarrow B_f, \\
 A_f &\leftarrow M^T \leftarrow B_f,
 \end{aligned}$$

which, when stabilized, recovers a previously stored pair (A_f, B_f) .

This BAM architecture has several key advantages which make it suitable for demonstration on our platform.

First, since recording the outer product of the input and output patterns corresponds to recording an interconnection hologram, this architecture is ideally-suited to an optical implementation.

Second, the matrix M^T is available optically, simply by using the interconnection hologram in reverse, putting a 2D pattern into the training plane, and observing the output in the image plane of the input plane.

Third, the pairs stored in the interconnection medium do not have to be linearly independent.

Fourth, updates to the input and output states can be performed asynchronously, which means that presenting information to the network at different wavelengths can be performed serially. This serial presentation is not required when presenting information to the input side of the network, which is wavelength-coded, because all signals which reach the output contain correct information. When the network is used in reverse, however, only one color contains correct information for each column. The only way to separate correct information from crosstalk is to present one color to the network at a time, and then read only the single column corresponding to that color.

Fifth, we don't have to have negative interconnections in the network (although they help), eliminating the need for dual rail logic.

Finally, the electronic feedback and sigmoid function already planned to implement the backpropagation architecture are completely suitable for BAM implementation.

5.3 . Demonstration Details

In the first demonstration, two different pairs of patterns will be stored in the network, as shown in Figures 11 and 12.

Figure 13 shows how a shifted version of the same SPARTA pattern used in each of the previous pattern pairs demonstrates the lack of crosstalk and space variance which is required for a 4D system.

The same two pairs can be recorded in a 3D network by working with a single wavelength and removing the wavelength coding of the input plane by illuminating the entire plane with a single color. Figures 14 and 15 show these two patterns, which have the same spatial structure as those recorded in the 4D network, but without the wavelength coding.

When a shifted version of the SPARTA pattern is presented to the 3D network in which the two pairs shown in Figures 14 and 15 have been stored, both output patterns, AFOSR and SHB, will appear overlapped in the output plane, showing the presence of crosstalk in a 3D network. The expected output is shown in Figure 16.

Once the electronic part of our network has been implemented, BAM operation can be demonstrated by presenting a partial input to the network and showing recovery of the "nearest" associated pair. Using PART of SPARTA is an appropriate way to demonstrate this property as shown in Figure 17. In the initial demonstration of BAM operation, only a single pair need be stored. In a more complete demonstration we would store a large number of pattern pairs, and then show retrieval of the pair with an input pattern most similar to a noisy input.

5.4 Summary of the Demonstration Plans

In the near term, demonstrating two properties of our 4D neural network will make an effective interim demonstration: the association of two patterns, for example, the letters SPARTA and AFOSR, and showing that shifting SPARTA in either the wavelength-coded or Bragg-coded direction produces no output, *i. e.*, no crosstalk. At the conclusion of the entire set of these experiments, we will have demonstrated all of the important characteristics needed to achieve a working neural network:

1. Association of pairs of patterns demonstrated using wavelength-coded inputs and 4D holographic connections,
2. Crosstalk between connections eliminated in both Bragg and wavelength-coded directions,
3. Bidirectional associative memory operation demonstrated,
4. Architecture combining optical and electronic components scalable to extremely large network sizes.

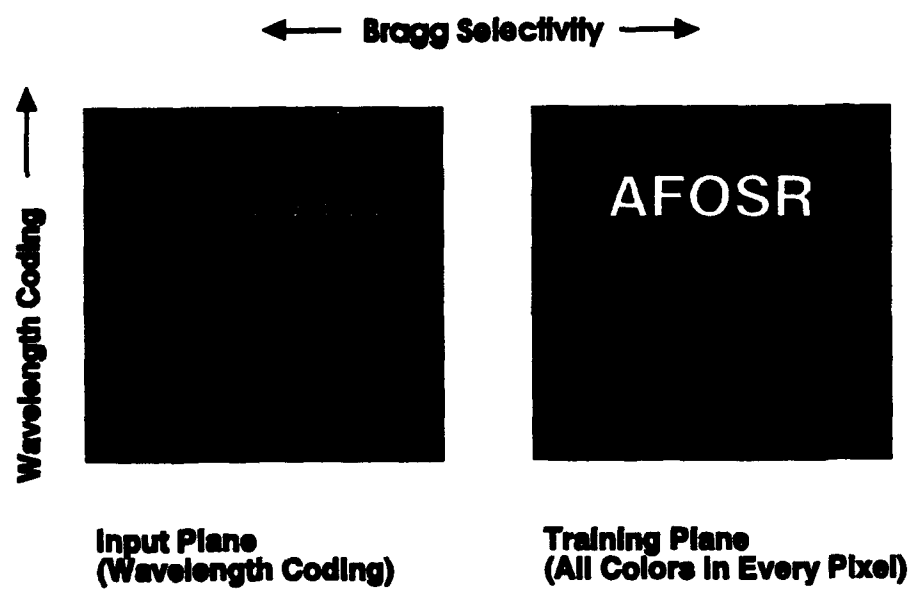


Figure 11. First pair to be stored in the 4D interconnection medium.

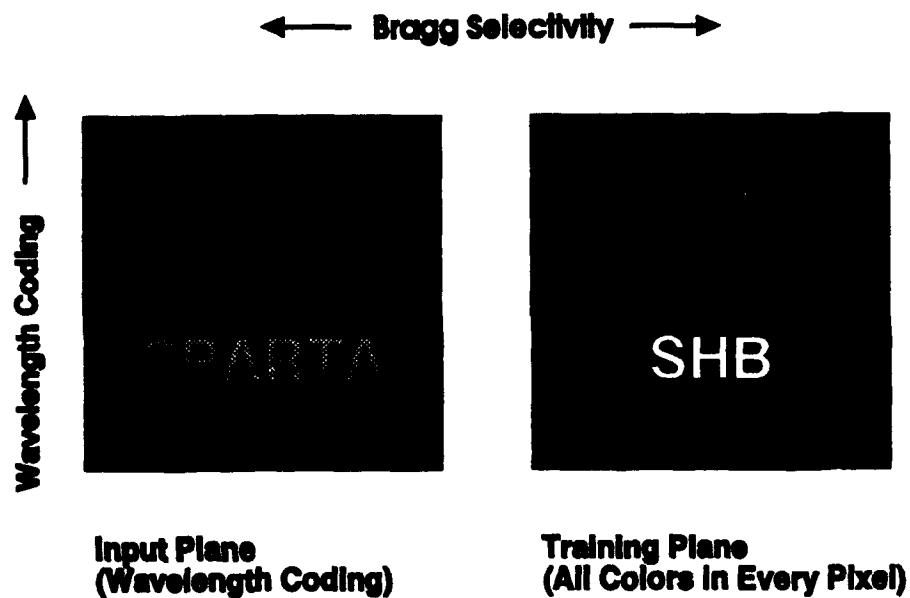


Figure 12. Second pair to be stored in the 4D interconnection network.

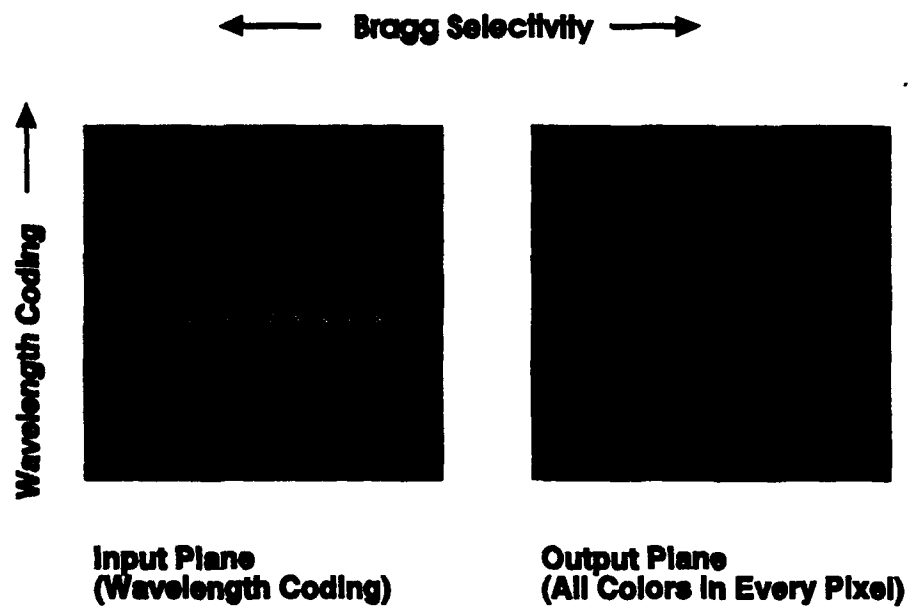


Figure 13. Input and response showing no crosstalk in the wavelength-coded direction in the 4D interconnection medium.

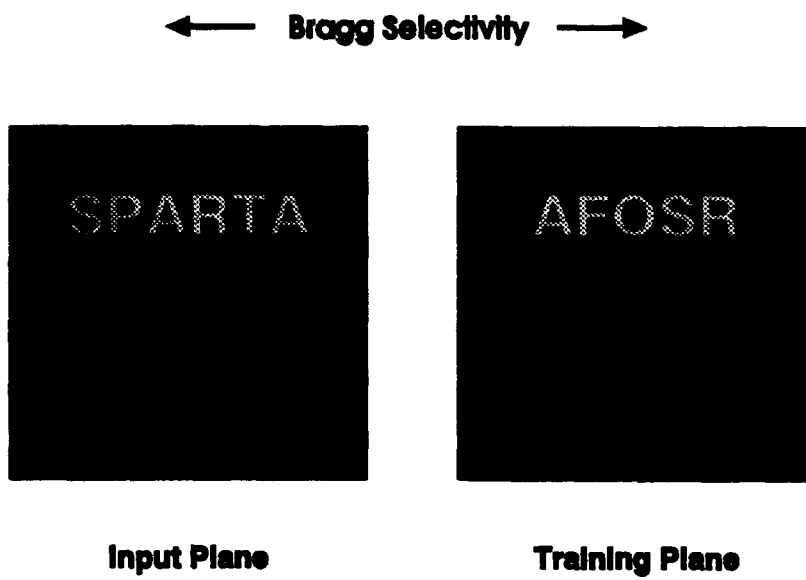


Figure 14. First pair to be stored in the 3D interconnection medium.

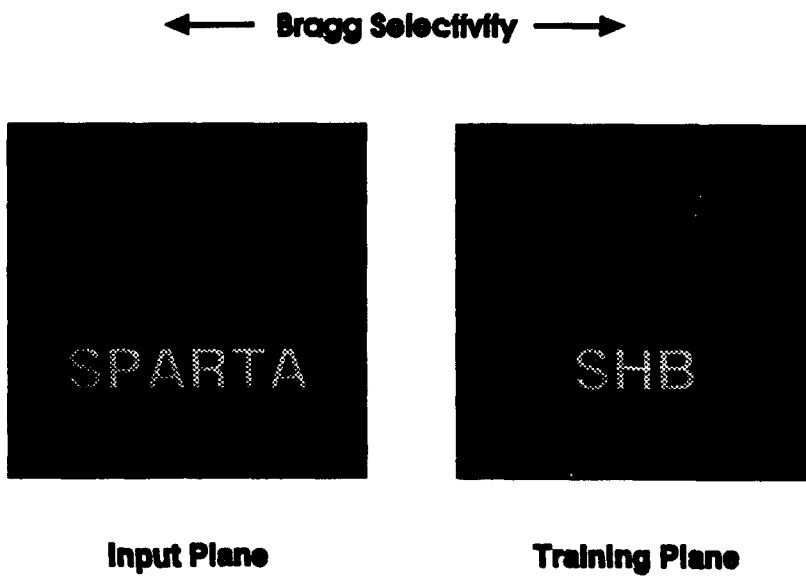


Figure 15. Second pair to be stored in the 3D interconnection medium.

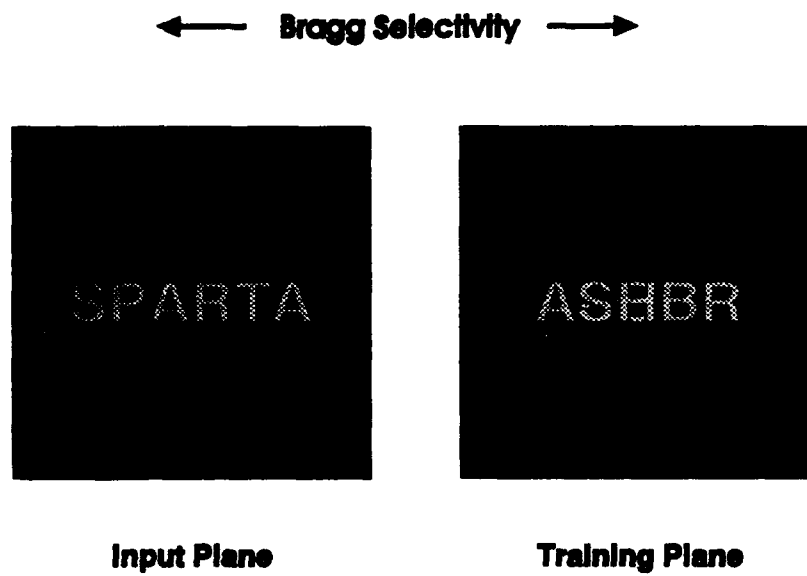


Figure 16. Response to a shifted version of SPARTA by the 3D network, illustrating the presence of crosstalk in the output.

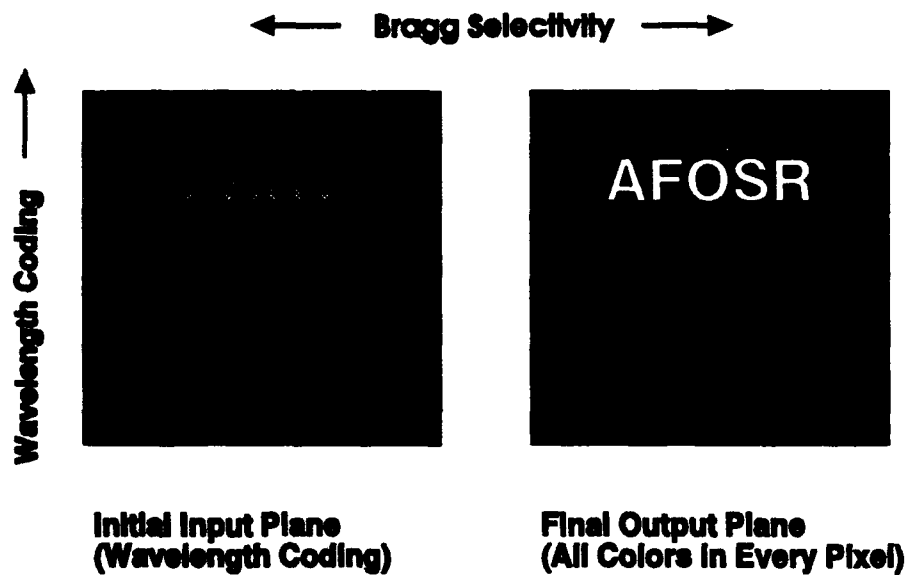


Figure 17. Partial pattern to be presented to the network and the expected convergence to the complete stored pattern pair.

6 Summary of Progress Achieved So Far

At this midpoint in the program we have completed the assembly of the optical system, laser, cryostat and we have synthesized the SHB material required. Holographic tests performed so far have demonstrated most of the aspects which are key to the operation of the neural network system. Almost all the key system components have been selected and will soon be inserted into the system. No aspects of the tests performed so far have indicated that any limitations exist in our initial designs or projections of performance for the short or the long term. The effort of the next year will be principally directed at making the complete system operational and performing the tests which will verify that the system exhibits the fundamental properties required for the operation of a neural network.

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